Control of Electromigration in Metallic Thin Films for Suppressing Interconnection Failures and Fabricating Fine Materials

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論 文 内 容 要 旨

Chapter 1　Introduction

Modern electronic devices are composed of a number of components giving complex electronic functions with miniaturization. With downscaling of a line cross-section in interconnections which increases current density in a metal line, electromigration (EM), a physical phenomenon of atomic diffusion in metals due to electron flow with high density, has raised issues for electronic reliability through the formation of EM damages which are voids and hillocks. The formation of voids/hillocks causes the open/short circuit by depletion/accumulation of atoms. To date, the threat of EM in interconnections has been discussed through the influencing factors using measures such as median time to failure (MTF) for EM lifetime, threshold current density, j_{th}, for the critical value above which EM damages initiate, and atomic flux divergence (AFD) where nonzero AFD forms EM damages. EM behavior is influenced by the following factors: thin film characteristics corresponding to material and crystal texture, passivation characteristics including material and thickness, geometrical shape of interconnections, and operating conditions such as current density and temperature. With clarifying influencing factors of EM behavior, the versatility of EM by controlling EM behavior can be enhanced; the prevention of EM contributes to suppressing interconnection failures, whereas the utilization of EM works for the fabrication of fine materials. The quantification of factors influencing EM behavior is required to control EM behavior, but some key factors which have not been quantified yet exist.

The present thesis aimed to propose control ways of EM behavior through the quantitative studies of the following factors: passivation thickness in Chapter 2, material combination around a corner having an interface composed of dissimilar metals in Chapter 3, operating current and discharging behavior of fabricated fine materials in Chapters 4 and 5. The control ways in prevention and utilization of EM closely relate each other; suppression of interconnection failures and fabrication of Al fine materials were demonstrated by decelerating and accelerating atomic diffusion in EM, respectively. To reveal respective ways to mitigate and enhance EM in suppression and fabrication contributes to advance in EM works.

Chapter 2　Effect of Passivation Thickness on Electromigration Damage in a 1D Metal Line

In Chapter 2, the strategy was proposed for determining the suitable passivation thickness to increase the threshold length product $j_{th}{\cdot}l$ against EM damages. The product $j_{th}{\cdot}l$ is a measure of the EM resistance, above which EM damages occur. Although the effect of passivation thickness on the EM resistance has been reported, the saturation mechanism with increasing passivation thickness has not been reported. The mechanism was clarified through the experiment by using $j_{th}{\cdot}l$ and through the discussion by considering the critical tensile stress in the circumferential direction at the inner wall of a long cylindrical tube as a model. The ideal value of $j_{th}{\cdot}l$ for the limiting case with infinite passivation thickness is determined based on the analysis. In practice, the passivation should be deposited with thickness determined based on the required $j_{th}{\cdot}l$ in the proposed model for suppressing interconnection failures. The deposition of suitable passivation thickness determined by the proposed model contributes to enhancing the back flow and increasing the allowable atomic density. Chapter 2 proposes the control way of EM-induced atomic flux for preventing the initiation of EM damages by determining suitable passivation thickness.

Chapter 3　Theoretical Consideration of Electromigration Damage around a 2D Right-Angled Corner

In Chapter 3, the theoretical considerations treating analytical solution of the EM damages around a right-angled corner composed of dissimilar single-crystal metals like via structure in an interconnection without/with passivation were conducted as the 2D EM problem. The theoretical considerations are for studying the effect of material combination of dissimilar metals on EM behavior; Materials 1 and 2 are defined as a vertical via and a horizontal line, respectively. So far, a right-angled corner composed of dissimilar metals without passivation except for an interface has been theoretically analyzed by using AFD. At the interface, the component of the atomic flux perpendicular to the interface is not continuous and AFD based on differentiation of the atomic flux cannot be obtained, whereas the component of the electron flow perpendicular to the interface is continuous. Thus, EM behavior at the interface was not able to be theoretically analyzed in the previous study. Unfortunately, the EM damages are enhanced at the interface and general interconnections have passivation. Also, the consideration of the material combination expressed by the ratio ρ_1/ρ_2 of electrical resistivities in Materials 1 and 2 is important, because the material combination significantly affects the EM behavior by varying current density distribution. The theoretical approaches for analyzing EM behavior, which can treat an interface around a corner composed of dissimilar metals without/with passivation, were proposed. Evaluations of the volume of accumulation/depletion of atoms at the interface without passivation and the atomic density distribution around a corner with passivation were conducted. Several countermeasures against the EM damages, which were obtained through the proposed theoretical analyses, were proposed as follows:

1) In case of the EM damage at the interface around a right-angled corner without passivation, the effect of material combination on the accumulation or depletion of atoms was clarified. For reducing the EM damage, lower ρ_1 and higher ρ_1/ρ_2 were recommended in Material 1, and lower ρ_2 and higher ρ_1/ρ_2 were recommended in Material 2.
2) The atomic density distribution around a passivated right-angled corner was theoretically analyzed. It was found that the EM damages in Material 1 would initially be formed at the corner. In Material 2, the EM damages would initially be formed near the interface far from the corner, even though the current density was concentrated at the corner. Through the analyses of the respective atomic density distributions for Materials 1 and 2, following countermeasures to increase j_{th} were proposed. Reduction of the material properties $N_0|Z^*|\rho/(\kappa\Omega)$ increases j_{th}; where N_0 is the atomic density under the stress-free conditions, Z^* is the effective valence, κ is the effective bulk modulus and Ω is the atomic volume. In contrast, with respect to the effect of the material combinations, a lower ρ_1 and a higher ρ_2 should be used to increase j_{th} in Material 2. More intriguingly, the countermeasure for increasing the EM resistance with respect to material combinations differs with that described in 1). In the case of the structure without passivation, the singularity parameter ξ subjected to ρ_1/ρ_2 should be increased to increase the EM resistance. However, in the case of the structure with passivation, it is recommended to decrease ξ for increasing the EM resistance. Chapter 3 proposes the control way for suppressing interconnection failures by leveling EM-induced atomic flux around a corner through the theoretical considerations on material combination in an interconnection.

Chapter 4 Structure for Increasing Fabrication Performance of Free-Standing Fine Materials

In Chapter 4, the new structures were proposed to improve the existing fabrication technique for Al fine materials by EM (the EM technique) and to increase the fabrication performance of Al fine materials for generating long wires. To advance the EM technique, the build-up structure and the embedded structure were developed. The findings in two approaches are as follows:
1) The build-up structure composed of two Al layers was developed for accomplishing huge production of Al fine materials. Through the demonstration of simultaneously fabricating two Al micro-materials, the ability for huge production of Al fine materials in the build-up structure was represented.
2) The embedded structure was developed as a countermeasure against current leakage with TiN conductive passivation. The present structure was embedded into Si wafer for confining current flow and for increasing fabrication performance of a free-standing and vertically-oriented Al fine material in the EM technique. The fabrication of Al micro-materials was demonstrated using the embedded structure and the fabrication performance was evaluated by introducing the threshold current, which was inspired by j_{th} in the prevention of EM. As a result, the proposed embedded structure is superior to the previous structure with respect to the fabrication performance. The threshold current for fabricating an Al micro-material using the

embedded structure was lower than that for the previous structure. Chapter 4 proposes the control ways of driving force of EM and the conditions for fabrication of fine materials by designing sample structure.

Chapter 5 Mechanism of Bending Phenomenon in Free-Standing Al Micro-Wires

In Chapter 5, for creating a straight wire, the mechanism of the irregular bending phenomenon of an Al micro-wire was elucidated through the structural analyses using focused ion beam system and scanning transmission electron microscope. As the problematic subject, the clarification of the irregular bending phenomenon is significantly important for applying to some devices. In this chapter, the kinking phenomenon was categorized to three types: an Al micro-wire was bent at grain boundaries (GBs) (Type I), without GBs (Type II), and at a location except for GBs (Type III). In Type I, the kinking phenomenon was explained by the changing orientation with switching to another GB. In Type II, the net of dislocations and the clusters of Al_2O_3 like γ-alumina would act for kinking. The net of dislocations indicated that an Al micro-wire was plastically deformed. The clusters of γ-alumina would be formed by the oxygen diffusion under high temperature, and would contribute to changing orientation. As a result, the bending was caused with generating the local strain in a wire. In Type III, an Al micro-wire was kinked by similar mechanism in Type II. The curve and collapse would be caused by the transecting difference in the growth rate. Some proposed countermeasures against bending phenomena, which are structurally analyzed in this chapter, give a potential to create straight wires by controlling atomic diffusion due to EM. The proposed hypotheses could assist with future works for clarifying bending mechanisms. Chapter 5 proposes the potential for controlling the shape of Al micro-wires by controlling driving force of EM governing the growth rate of the wires.

Chapter 6 Conclusions

In conclusion, the present thesis proposed the control ways of EM behavior for suppressing interconnection failures and fabricating metallic fine materials by utilizing above examined factors as control parameters of EM behavior. These original approaches contributed to lay groundwork with keen insight in controlling EM behavior for suppressing interconnection failures and fabricating fine materials. In the present thesis, atomic diffusion of Al was mainly targeted but the knowledge for controlling EM behavior could be applied to other metals. The present thesis comprehensively advances fundamental studies for solving incoming technological problems in ICs and for providing versatile methods in utilization of EM.

論文審査結果の要旨

電子デバイスの金属薄膜配線において，高密度電子流に起因して金属原子の拡散現象であるエレクトロマイグレーション（以下 EM）が起きることが知られている。原子の損失によるボイドや蓄積によるヒロックの形成は配線の断線や回路の短絡を招くため，当該損傷抑制は重大な課題である。著者は，アルミニウムを代表とした金属原子の EM に対する諸構造因子の影響を定量的に解明し，損傷抑制に加え EM を有効利用した金属微細材料創製の基盤となる原子流制御技術を提案した。本論文は，これらの研究成果をまとめたものであり，全編 6 章からなる。

第 1 章は序論であり，本研究の背景，目的および構成を述べている。

第 2 章では，絶縁保護膜厚さとアルミニウム原子の EM 挙動の関係を通電試験と考察により定量的に明らかにしている。EM 損傷が生じる臨界の電流密度であるしきい電流密度が絶縁保護膜厚さの増大に伴い増加し，やがて飽和する現象について，原子蓄積に起因して絶縁保護膜に作用する応力を理論モデルに導入することで，当該飽和現象を説明することに成功している。これは効果的な損傷抑制のための EM 制御の基盤となる重要な成果である。

第 3 章では，異種金属接合角部を有する配線構造を対象として，電流密度集中の影響下における EM を扱い，配線材料の組合せが EM による接合面での損傷蓄積と角部近傍での原子濃度分布に及ぼす影響を理論解析により検討している。これに基づき絶縁保護膜の有無による原子流の変化を明らかにし，当該角部における EM 損傷抑制への対策手法を提案している。これは EM 損傷抑制に資する貴重な成果である。

第 4 章では，EM 制御による金属微細材料創製を扱い，サンプル構造設計に基づく EM の促進による効率的な金属微細材料創製手法を提案している。まず拡散バリア層を介した金属薄膜の積層構造を用いることが，当該創製の有効な基礎技術となる可能性を有することを示している。また絶縁基板へ金属薄膜配線を埋め込むことで，電子流を金属薄膜配線内へ集中させることを可能とし，創製に要する臨界の電流であるしきい電流を約 1/10 に低減できることを示し，埋込構造による金属微細材料創製の有効性を検証している。これらはサンプル構造設計に基づいた EM 制御による金属微細材料創製の他に先駆けた成果である。

第 5 章では，EM で人工微細孔から原子を排出して創製したアルミニウムマイクロワイヤが屈曲する現象を対象とし，その機構を組織分析により検討している。EM によるアルミニウム原子の拡散挙動を電流量と温度により制御することで，屈曲現象の発生を緩和できる可能性を実験的に示唆し，これを踏まえ原子排出速度に着目したマイクロワイヤ形状制御の基礎手法を提案している。これは，化学センサや微細デバイス，光回路等への応用を指向した EM 制御による金属微細材料の形状制御のための新たな成果である。

第 6 章は結論である。

以上要するに本論文は，EM によるアルミニウム等金属原子の拡散挙動に及ぼす諸構造因子の影響を探究し，損傷抑制と金属微細材料創製に利用できる原子流制御技術の基礎を開拓したものであり，ナノメカニクスおよび機械工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。